Thermal Contraction and Fitting Test

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I. Introduction

While developing a superconducting solenoid for the Front End of the Proton Driver, significant attention must be paid to the issues of arranging for a prestress in the solenoid's coil. To save radial space, it seems efficient to use thermal expansion (and/or shrinkage) to make a press-fit of two concentric cylinders.

Preliminary analysis of possible schemes of prestress in the solenoids requires using cylinders with outer radius of ~ 100 mm and wall thickness of ~ 5 mm. Typical overlap is about 50 mkm. This requires quite modest temperature difference of ~ 100 deg. C to make the fit.

Before using this fitting technique during solenoid assembly, one must know how difficult (or easy) is this technique and what requirements should be for the assembled parts dimensions.

Another issue that must be understood is what is allowed tangential compression stress in the inner part. For sure, it must be below yield stress, but if the inner part is thin in radial direction, compression instability can be a problem. For example, for a pipe exposed to outside pressure, limit of this pressure is defined by the expression:

$$P_{cr} = \frac{E \cdot h^3}{4(1-\mu^2) \cdot R^3}$$

For the stainless steel pipe with radius of 25 mm and wall thickness of 2 mm this gives P_{cr} = 28.5 MPa, which is much less than yeald limit of ~ 250 MPa. Because in our case we have another pipe that helps to increase stability, we do not expect this low limit, but to check on this issue is imperative before we can plan winding coil on a thin bobbin.

To get some confidence on both issues, we have planned and implemented a test where the two pipes were assembled by using thermal shrinkage. As a useful side effect, we checked on coefficients of thermal expansion of stainless steel and found integrated thermal contraction coefficient from room temperature to LN temperature.

II. Thermal Properties of Steel and Inconel

Before the fitting test could start, we needed some confidence in knowing coefficients of thermal shrinkage. Because Inconel 625 was considered as the choice material for the coil bobbin, and its integrated shrinkage coefficient was not known, we wanted to find it with some degree of confidence. To be sure the measurement method is correct, we've chosen stainless steel as a reference material.

Length of the stainless and Inconel-625 cylinders was measured (with some statistics) at room temperature (20°C) and at LN temperature (~ 80 K). Integrated contraction coefficient of stainless steel (averaged among 10 measurements) was found equal to **0.0028**, which is exactly what the tabulated value of integrated thermal contraction is.

For the Inconel 625 the integrated (300 K – 80 K) contraction coefficient found using the same method is **0.0021**.

III. Pipe Description

Inner Pipe

Nominal dimensions of the inner pipe were (in inches):
ID = 1.748, OD = 1.904 $^{+0.001}$, L = 6.0

Measured dimensions:
max ID = 1.7484, min ID = 1.7467
There was systematic increase (although small) of the inner diameter from one end of the pipe to another (conical shape).
max OD = 1.9052, min OD = 1.9045

Outer Pipe

Nominal dimensions (in inches):
ID = 1.900$_{-0.001}$, OD = 2.250 REF, L = 4.0
Measured dimensions:
max ID = 1.8997, min ID = 1.8986
There was systematic increase (although small) of the inner diameter from one end of the pipe to another (conical shape)
max OD = 2.2490, min OD = 2.2500

IV. Fitting Test

The inner stainless steel pipe was cooled down to LN temperature of ~ 80 K. The outer pipe was heated up to ~ 50 deg C.

For SS 304 measured (by us) integrated 300 K – 80 K contraction is 0.0028 (the same is the tabulated value). So, we expect max OD = 1.9052*(1-0.0028) = 1.8998

Coefficient of thermal expansion of SS at room temperature is $1.6*10^{-5}$. After heating to 50 deg C, the min ID of the outer pipe becomes

$$ID = 1.8986*(1+30*1.6*10^{-5}) = 1.8995.$$

Because min ID fro the outer pipe is larger than the max OD of the inner pipe, the test must fail. It did fail.

To improve the situation, it was decided to remove 2 mils from the outer diameter of the inner pipe. Then, after heating to 50 deg C, the outer diameter of the inner pipe must become 1.9032. Measurements show this diameter at room temperature of **OD = 1.9025**. This will bring the expected diameter at LN temperature to 1.8971”. AS a result we will have ~ 2 mils of difference between ID and OD, and the pipes can be fitted together.

The fitting test was repeated with max T ~ 90 deg C, and was successful. Estimated value of ID is 1.9007, OD = 1.8971. The difference is ~ 3.6 mils or ~ 90 mkm.
The fitting went very well if it is done quickly so that temperature does not change much.

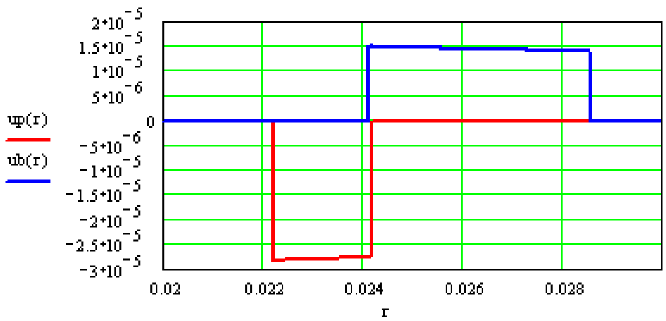
After the two pipes were put together, the inner diameter of the inner pipe has changed in the following way:

1. At the ends of the inner pipe that were not covered with the outer pipe (1/2” from the end of the outer pipe) dimensions did not change at all.

2. Inside the limits of the outer pipe ID = 1.7451, which is less than 1.7475 of the average diameter from the first set of measurements. **Expected deformation is 2.4 mil.**
3. The outer diameter of the outer pipe became OD = 2.2507, which is larger than the average 2.2495 from the first set of measurements. **Expected deformation is 1.2 mil.**

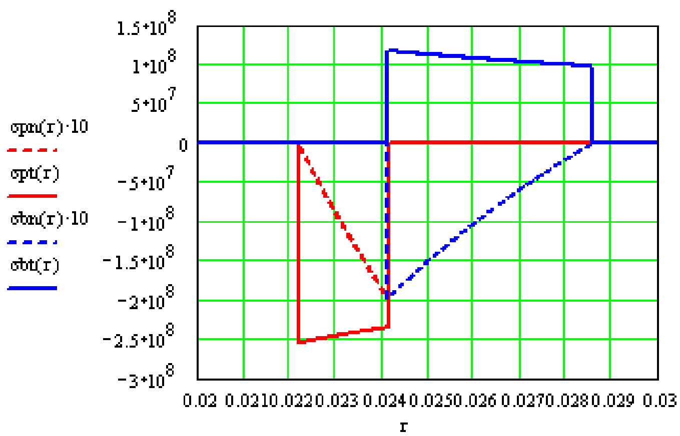
V. Modeling results

Results of modeling of the system using two-layer MathCad model are shown below:



All dimensions in this picture are in meters and deformations of **radius** is calculated. Deformation of the inner pipe (inner and outer **diameter**) is about 55 mkm or 2.2 mil. Deformation of the outer pipe is ~ 29 mkm or 1.1 mil

The measured deformations are well compared with the expected one. The next figure shows the normal and tangential stress distribution (pay attention on the scale of the normal stress).



Normal stress reaches ~ 20 MPa on the border between the two layers. The tangential compression stress in the inner pipe reaches 250 MPa, which is already on the level of the Yield stress. Although this stress is much higher than the limit of stability in air, having outside pipe in a tight contact with the inner one stabilizes the inner pipe, so we did not see any signs of instability here.
This fact allows us using higher tension force during coil winding (if needed).

VI. Summary

1. It was possible to use difference in temperature of the inner and outer pipes to assemble the pair with overlap of about 3.5 mils. Hence, this technique can be used for prestress application.
2. Measurements of the inner and outer diameters can be made with reasonable precision; the results of measurements agree well with prediction made by modeling.
3. Although tangential compression stress in the inner pipe is very high, no instability effects have been noticed, so larger wire tension force can be used, if needed, or thinner pipe wall can be used with some care.